

# Results of MAGIC on Galactic sources

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**Abstract.** MAGIC is a single-dish Cherenkov telescope located on La Palma (Spain), hence with an optimal view on the Northern sky. Sensitive in the 30 GeV – 30 TeV energy band, it is nowadays the only ground-based instrument being able to measure high-energy  $\gamma$ -rays below 100 GeV. We review the most recent experimental results on Galactic sources obtained using MAGIC. These include pulsars, binary systems, supernova remnants and unidentified sources.

**Keywords:** Very High Energy Gamma-ray astronomy; Galactic sources; MAGIC telescope

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## INTRODUCTION: THE MAGIC TELESCOPE

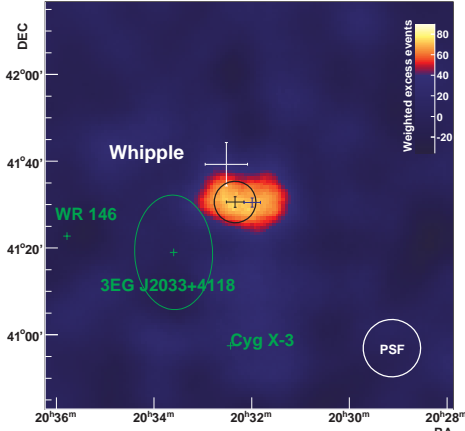
The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope is a last-generation instrument for very high energy (VHE,  $E \geq 50 - 100$  GeV)  $\gamma$ -ray observation exploiting the Imaging Air Cherenkov (IAC) technique. It is located on the Roque de los Muchachos Observatory ( $28^\circ 45' 30''$ N,  $17^\circ 52' 48''$ W, 2250 m above sea level) in La Palma (Spain). This kind of instrument images the Cherenkov light produced in the particle cascade initiated by a  $\gamma$ -ray in the atmosphere. MAGIC incorporates a number of technological improvements in its design and is currently the largest single-dish telescope (diameter 17 m) in this energy band, yielding the lowest threshold (55 GeV with the nominal trigger, 25 GeV with the pulsar trigger). Since February 2007, MAGIC signal digitization has been upgraded to 2 GSample/s Flash Analog-to-Digital Converters (FADCs), and timing parameters are used during the data analysis [1]. This results in an improvement of the flux sensitivity from 2.5% to 1.6% (at a flux peak energy of 280 GeV) of the Crab Nebula flux in 50 hours of observations. The relative energy resolution above 200 GeV is better than 30%. The angular resolution is  $\sim 0.1^\circ$ , while source localization in the sky is provided with a precision of  $\sim 2'$ . MAGIC is also unique among IAC telescopes by its capability to operate under moderate illumination [2] (i.e. moonlight and twilight). This allows to increase the duty cycle by a factor 1.5 and a better sampling of variable sources is possible. The construction of a second telescope is now in its final stage and MAGIC will start stereoscopic observations in the near future.

## RECENT RESULTS ON GALACTIC OBJECTS

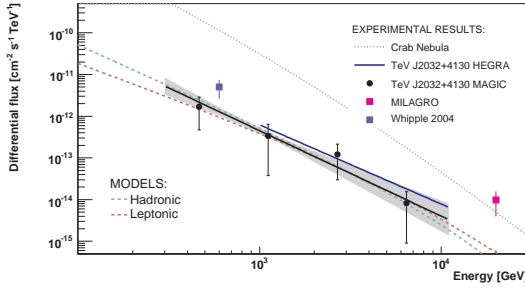
The physics program developed with the MAGIC telescope includes both, topics of fundamental physics and astrophysics. Regarding Galactic observations, MAGIC has discovered four new VHE  $\gamma$ -ray sources [3, 4, 5, 6] and studied in detail eight of the previously known [7, 8, 9, 10, 11, 12, 13, 14]. In this paper we highlight our latest contributions to Galactic astrophysics. The results from extragalactic observations are presented elsewhere in these proceedings [15].

### TeV 2032+4130

The TeV source J2032+4130 was the first unidentified very high energy (VHE)  $\gamma$ -ray source, and also the first discovered extended TeV source, likely to be Galactic [16]. The field of view of TeV J2032+4130 was observed with MAGIC for 93.7 hours of good-quality data, between 2005 and 2007 [8]. The source is extended with respect to the MAGIC PSF (see Figure 1). Its intrinsic size assuming a Gaussian profile is  $\sigma_{\text{src}} = 5.0 \pm 1.7_{\text{sta}} \pm 0.6_{\text{sys}}$  arcmin. The energy spectrum is well fitted ( $\chi^2/n.d.f = 0.3$ ) by the following power law:  $\frac{dN}{dE dA dt} = (4.5 \pm 0.3) \times 10^{-13} (E/1 \text{ TeV})^{-2.0 \pm 0.3} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ . Quoted errors are statistical, the systematic error is estimated to be 35% in the flux level and 0.2 in the photon index [10]. The MAGIC energy spectrum (see Figure 2) is compatible both in flux level and photon index with the one measured by HEGRA, and extends it down to 400 GeV. We do not find any spectral break, nor any flux variability over the 3 years of MAGIC observations.



**FIGURE 1.** Skymap of  $\gamma$ -ray candidate events (background-subtracted) for energies above 500 GeV. The MAGIC position is shown with a black cross. Also shown are the last positions reported by Whipple and HEGRA.

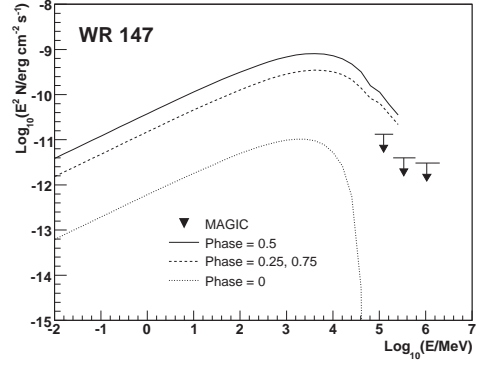


**FIGURE 2.** Differential energy spectrum from TeV J2032+4130. The shaded area shows the  $1\sigma$  error in the fitted energy spectrum. The flux observed by Whipple in 2005 and in the Milagro scan are marked with squares. The light line shows the HEGRA energy spectrum. Theoretical one-zone model predictions are depicted with dashed lines.

### Wolf-Rayet binaries

WR stars display some of the strongest sustained winds among galactic objects with terminal velocities reaching up to  $v_\infty > 1000 - 5000$  km/s and also one of the highest known mass loss rate  $\dot{M} \sim 10^{-4} \dots 10^{-5} M_\odot/\text{yr}$ . Colliding winds of binary systems containing a WR star are considered as potential sites of non-thermal high-energy photon production, via leptonic and/or hadronic process after acceleration of primary particles in the collision shock (see, e.g., [17]).

We have selected two objects of this kind, namely WR 147 and WR 146, and observed them for 30.3 and 44.5 effective hours, respectively [7]. No evidence for VHE  $\gamma$ -ray emission has been detected in either case,



**FIGURE 3.** Inverse Compton (IC) spectra of WR 147 for orbital phases 0, 0.25, 0.5 and 0.75 [17] together with MAGIC experimental upper limits.

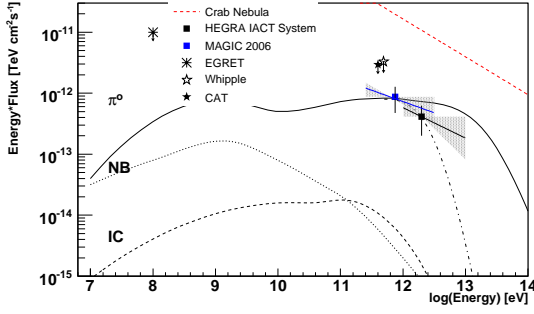
and upper limits to the emission of 1.5, 1.4 and 1.7% (WR 147) and 5.0, 3.5 and 1.2% (WR 146) of the Crab Nebula flux are derived for lower energy cuts of 80, 200 and 600 GeV, respectively. These limits are shown in Figure 3 for the case of WR 147, compared with a theoretical model [17].

### Cassiopeia A

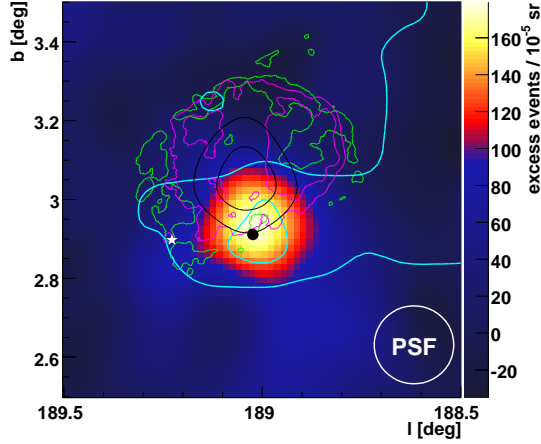
We observed the shell-type supernova remnant (SNR) Cassiopeia A during 47 good-quality hours, and detected a point-like source of VHE  $\gamma$ -rays above  $\sim 250$  GeV [9]. The measured spectrum is consistent with a power law with a differential flux at 1 TeV of  $(1.0 \pm 0.1_{\text{stat}} \pm 0.3_{\text{sys}}) \times 10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$  and a photon index of  $\Gamma = 2.4 \pm 0.2_{\text{stat}} \pm 0.2_{\text{sys}}$ . The spectrum measured about 8 years later by MAGIC is consistent with that measured by HEGRA [18] for the energies above 1 TeV, i.e., where they overlap (see Figure 4). Our results seem to favor a hadronic scenario for the  $\gamma$ -ray production, since a leptonic origin of the TeV emission would require low magnetic field intensities, which is in principle difficult to reconcile with the high values required to explain the rest of the broad-band spectrum. However, hadronic models [19] predict for the 100 GeV – 1 TeV region a harder spectrum than then measured one.

### IC 443/MAGIC J0616+225

We have detected a new source of VHE  $\gamma$ -rays located close to the Galactic Plane, namely MAGIC J0616+225 [4], which is spatially coincident with the SNR IC 443. The measured energy spectrum is well fitted ( $\chi^2/n.d.f. = 1.1$ ) by the following power

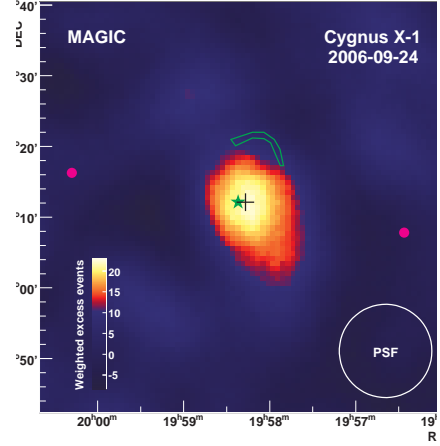


**FIGURE 4.** Spectrum of Cas A as measured by MAGIC. The upper limits given by Whipple, EGRET and CAT are also indicated, as well as the HEGRA detection. The MAGIC and HEGRA spectra are shown in the context of the model by [19].



**FIGURE 5.** Sky map of  $\gamma$ -ray candidate events (background subtracted) in the direction of MAGIC J0616+225 for an energy threshold of about 150 GeV. Overlaid are  $^{12}\text{CO}$  emission contours, contours of 20 cm VLA radio data, X-ray contours and  $\gamma$ -ray contours from EGRET. The white star denotes the position of the pulsar CXOU J061705.3+222127. The black dot shows the position of the 1720 MHz OH maser.

law:  $\frac{dN}{dE dA dt} = (1.0 \pm 0.2) \times 10^{-11} (E/0.4 \text{ TeV})^{-3.1 \pm 0.3} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ . MAGIC J0616+225 is point-like for MAGIC spatial resolution, and appears displaced to the south of the center of the SNR shell, and correlated with a molecular cloud [20] and the location of maser emission [21] (see Figure 5). There is also an EGRET source centered in the shell of the supernova remnant. The observed VHE radiation may be due to  $\pi^0$ -decays from interactions between cosmic rays accelerated in IC 443 and the dense molecular cloud. A possible distance of this cloud from IC 443 could explain the steepness of the measured VHE  $\gamma$ -ray spectrum.



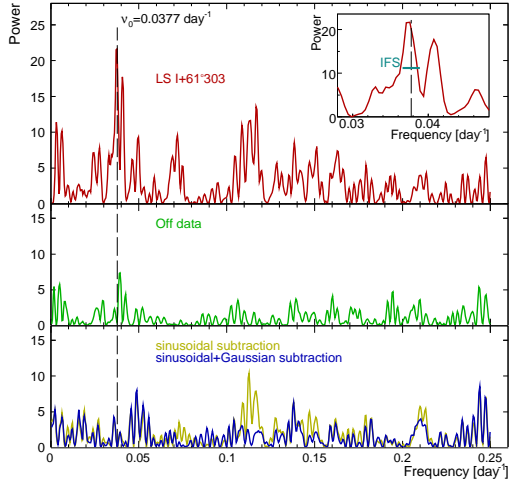
**FIGURE 6.** Skymap of  $\gamma$ -ray excess events (background subtracted) above 150 GeV around Cygnus X-1 corresponding to the flare detected on 2006-09-24. The cross shows the best-fit position of the  $\gamma$ -ray source. The position of the X-ray source and radio emitting ring-like are marked by the star and contour, respectively.

### *Cygnus X-1*

Cygnus X-1 is the best established candidate for a stellar mass black-hole (BH) and one of the brightest X-ray sources in the sky. We have observed it for 40 hours along 26 different nights between June and November 2006. Our observations have imposed the first limits to the steady  $\gamma$ -ray emission from this object, at the level of 1% of the Crab Nebula flux above  $\sim 500$  GeV. We have also obtained a very strong evidence ( $4.1\sigma$  post-trial significance) of a short-lived, intense flaring episode during 24th September 2006, in coincidence with a historically high flux observed in X-rays [22] and during the maximum of the  $\sim 326$ d super-orbital modulation [23]. The detected signal is point-like, consistent with the position of Cygnus X-1. The nearby radio-nebula produced by the jet interaction with the interstellar medium [24] is excluded as the possible origin of an eventual putative emission (see Figure 6).

### *LS I +61 303*

LS I +61 303 is a very peculiar binary system containing a main-sequence star together with a compact object (neutron star or black hole), which displays periodic emission throughout the spectrum from radio to X-ray wavelengths. Observations with MAGIC have determined that this object produces  $\gamma$ -rays up to at least  $\sim 4$  TeV [3], and that the emission is periodically modulated by the orbital motion ( $P_{\text{TeV}} = (26.8 \pm 0.2) \text{ d}$ ) [25] (see Figure 7). The peak of the emission is found always at

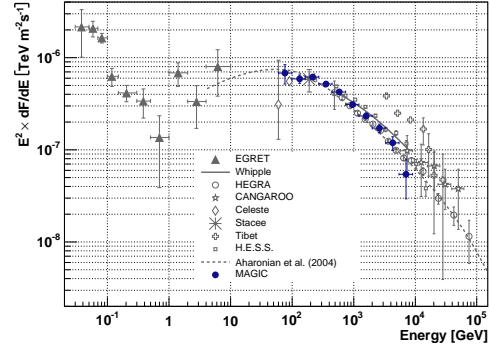


**FIGURE 7.** Lomb-Scargle periodogram for LSI+61303 data (upper panel) and simultaneous background data (middle panel). In the lower panel we show the periodograms after subtraction of a sinusoidal signal at the orbital period (light line) and a sinusoidal plus a Gaussian wave form (dark line). The vertical dashed line corresponds to the orbital frequency. Inset: zoom around the highest peak, which corresponds to the orbital frequency ( $0.0377\text{d}^{-1}$ ). Its post-trial probability is  $\sim 10^{-7}$ . The IFS is also shown.

orbital phases around 0.6–0.7. During December 2006 we detected a secondary peak at phase 0.8–0.9. Between October–November 2006, we set up a multiwavelength campaign involving radio (VLBA, e-EVN, MERLIN), X-ray (Chandra) and TeV (MAGIC) observations [26]. We have excluded the existence of large scale ( $\sim 100$  mas) persistent radio-jets, found a possible hint of temporal correlation between the X-ray and TeV emissions and evidence for radio/TeV non-correlation.

### Crab Nebula

The Crab Nebula is the standard candle for VHE astrophysics and as such, a big fraction of MAGIC observation time is devoted to this object. Out of it, we have used 16 hours of optimal data to measure the energy spectrum between 60 GeV and 8 TeV [10]. The peak of the SED has been measured at an energy  $E = (77 \pm 35)$  GeV (see Figure 8). The VHE source is point-like and the position coincides with that of the pulsar. More recently, thanks to a special trigger setup, we have detected pulsed emission coming from the Crab pulsar above 25 GeV, with a statistical significance of  $6.4\sigma$  [6]. This is the first time that a pulsed  $\gamma$ -ray emission is detected from a ground-based telescope, and opens the possibility of a detailed study of the pulsar’s energy cutoff, which will help elucidate the mechanism of high energy radiation in these objects.



**FIGURE 8.** SED of the  $\gamma$ -ray emission of Crab Nebula. The measurements shown below 10 GeV are by EGRET. In VHE  $\gamma$ -rays, measurements are from ground-based experiments.

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